U. S. ARMY
TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

TRECOM TECHNICAL REPORT 63-34

A FLIGHT INVESTIGATION OF PROFILE DRAG MEASUREMENTS

Task 1D121401A14203
(Formerly Task 9R38-11-009-03)
Contract DA 44-177-AMC-892(T)

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A Government review of this report has been completed by the U. S. Army Transportation Research Command. This investigation was conducted to compare the differences and limitations between two prominent methods of measuring profile drag and to offer possible explanations for these differences by the compilation and interpretation of actual flight test data.

From review of this report, the concluding remarks are considered to be justified and acceptable.

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A FLIGHT INVESTIGATION OF PROFILE DRAG MEASUREMENTS

Aerophysics Research Note No. 16

Prepared by
The Aerophysics Department
Mississippi State University

for
U. S. ARMY TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

CONTENTS

ILLUSTRATIONS

SYMBOLS

x, y	Co-ordinates
C_{D_0}	Profile drag coefficient
H	Total pressure
p	Static pressure
c	Chord
w	Height of rake
F	A correction factor (Ref. 3)
ρ	Density
U	Velocity
$G_1 = \frac{g_1 - p_\infty}{1/2 \rho U_\infty^2}$, $G_1 = 1$	outside the wake
g_1	Total head in wake = $p_1 + 1/2 \rho U_1^2$
g_∞	Freestream total head
α	Airfoil angle of attack

Subscript

∞	Freestream conditions
1	Conditions in the plane of measurement
av	Average
0	Sea level conditions

INTRODUCTION

In 1925 Betz published a report[1] on the study of wakes behind bodies and the determination of profile drags of airfoils by suitable measurements in the wake. Jones[2] in 1936 conducted a similar study and presented an alternative formula relating the profile drag of a wing section to the traverse of total head in the wake behind and conveniently near the wing section. The Jones formula has the merit of extreme simplicity and is at least as accurate as the Betz method. The wake velocity profile may be obtained by using either a comb of Pitot-static tubes connected to a multitube manometer or a traversing Pitot-static system. The latter has the advantage of being able to be dynamically balanced for local pressure changes and may be connected to a sensitive airspeed indicator, the only disadvantage being a possible change in flight conditions while the wake is being traversed. Another method is to connect a multitube Pitot comb to a multitube water manometer and to observe the reservoir level directly on a sensitive inclined tube. The integrating system has the advantage of being very simple, as only two readings are required to determine the profile drag. Due to changes in static pressure behind the airfoil and the effect of fuselage proximity, certain corrections must be applied to the integrating wake rake results. These corrections were determined for a number of airfoil sections in extensive wind-tunnel tests by Silverstein and Katzoff[3] in 1946, with the result that the integrating wake rake is commonly used in the United States for the determination of the profile drags of airfoils in flight. The use of the integrating wake rake by the author[4] to determine section profile drags in flight brought to light a number of inaccuracies which prompted a detailed study into profile drag measurements.

Profile drags were measured on two very different airfoil sections in flight using both the integrating wake rake favored by Silverstein and Katzoff and a traversing Pitot-static system. A direct comparison of the two methods was made and possible explanations for the differences presented. The tests were performed on a Schweitzer TG 3 sailplane (Figure 1) which had a fiberglass low-drag glove section fitted to the port wing (Figure 2) and on the starboard wing a rather unusual leading edge section which was used for laminar separation bubble investigation (Figure 3).

THE INTEGRATING WAKE RAKE

Two different integrating wake rakes were used in this test (Figure 4). They were 6-1/2 and 12 inches high with 40 and 27 equally spaced tubes respectively. The probe was attached to the trailing edge. Connections were made as shown diagrammatically in Figure 5, which gives, according to reference 3,

$$C_{D_0} = \frac{F}{C} w \frac{H_\infty - H_{1av}}{H_\infty - P_\infty} = \frac{F}{C} w \frac{P_\infty + \frac{1}{2}\rho_\infty U_\infty^2 - (P_1 + \frac{1}{2}\rho_1 U_{av}^2)}{\frac{1}{2}\rho U_\infty^2} .$$

Because the rake was connected against a trailing static probe and airspeed indicators were used, $\rho_1 = \rho_0$, $\rho_\infty = \rho_0$;

$$\therefore \quad C_{D_0} = \frac{F}{C} w \left(\frac{U_\infty^2 - U_{av}^2}{U_\infty^2} \right).$$

The factor F was found according to reference 3, and it is a function of C_{D_0}, airfoil thickness, distance of rake behind the trailing edge, and the proximity of the fuselage.

A number of flights were made, and the profile drag curve presented in Figure 6 was obtained. Because of the considerable scatter of the results, it was thought that perhaps the measurement of U_{av} was incorrect; therefore, an alternative system using the same rake was devised whereby the integrated wake total head was connected against the aircraft total head such that

$$C_{D_0} = \frac{F}{C} w \frac{H_\infty - H_{1av}}{H_\infty - P_\infty} = \frac{2Fw}{C} \left(\frac{\Delta p_i}{U_\infty^2} \right) .$$

Δp_i was initially measured with a Kollsman helicopter airspeed indicator with inconsistant results, and was later measured with a sensitive pressure gauge[4] which read Δp_i in inches of water. The results obtained using these two systems on the #1 test section are shown in Figure 7. Due to the large variation of results obtained using this small integrating wake rake, it was replaced by the large rake which, although less sensitive than the small one, insured that the wake was completely spanned. The results of the large rake on #1 section are also plotted in Figure 7.

The large integrating wake rake was then attached to the #2 test section and the $C_{D_0} \sim \alpha$ curve obtained with the rake in a certain position with respect to the section trailing edge. The rake was then moved vertically two inches with respect to the trailing edge, and the profile drag curve of the #2 section was obtained with the rake at the new position. The curves of $C_{D_0} \sim \alpha$ for both rake positions are shown in Figure 8.

THE TRAVERSING WAKE RAKE

To investigate the inconsistency of measuring the profile drag by means of an integrating wake rake, a traversing rake was constructed as shown in Figure 9. The Pitot-static system on the rake was dynamically balanced, the screw arrangement was driven by an electric motor, and a calibrated cog wheel activating a metering device gave the "Y" value above a certain zero to the nearest 0.001 inch. The total traverse was 12 inches, and the wake traverse time was normally 2 minutes. A static pressure probe was also mounted on the traversing platform and connected against aircraft total head to determine the static pressure variation in a plane through the wake. A number of mounts were constructed so that the total traversing range would be displaced vertically with respect to the airfoil trailing edge.

The wake velocity profiles were obtained in a few flights and, together with the static pressure variations, were plotted in Figure 10. From these profiles, the section profile drag was obtained using the following equation by Jones:

$$C_{D_0} = \frac{D}{\frac{1}{2}\rho U_\infty^2 c} = 2\int_{WAKE} \sqrt{G_1 - P_1}\left(1 - \sqrt{G_1}\right) d\left(\frac{y}{c}\right).$$

As this equation involves considerable calculation for each profile, the process was programmed for the IBM 1620 computer, which considerably decreased the data processing time (Appendix I). It can be seen from Figure 10 that in some cases the free-stream velocity is not the same above and below the wake; to overcome this problem, a mean line was drawn as shown in Figures 10 and 12. The profile drag results were plotted in Figures 11 and 13 and directly compared with the integrating wake rake results.

DISCUSSION

The poor repeatability of results using the integrating wake rake, clearly seen in Figure 7 for the #1 section and the scatter in the results for the #2 section (Figure 8), and the variation in profile drag with vertical position of the rake with respect to the section trailing edge indicate that profile drag results obtained using the integrating system tend to be unreliable. This unreliability was not due to the continually changing free-stream static pressure associated with sailplane flight testing, because the systems were dynamically balanced, but rather to the static pressure variation outside the wake. From the plot of static pressure through the wake in Figure 10, it is seen that the pressure remains reasonably constant through the wake region; but outside the wake, the static pressure exhibits deviations which correspond to the irregular free-stream velocity conditions. This means that, in the plane of measurement, equilibrium conditions do not exist and that, outside the wake, pressure recovery is not complete. The use of an integrating wake rake under such conditions tends to give misleading results. Of course, using the traversing wake rake under the same condition means that certain assumptions must be made. The most important of these is that, from the plane of measurement to infinity, equilibrium conditions are attained without further losses and that the profile drag of the section is contained entirely within the boundaries of the unsteady wake. Therefore, the traversing rake is used to obtain the wake velocity profile, and the limits of integration are taken as those regions where turbulent flow ceases and steady flow begins. These limits also correspond to the maximum velocity in the plane of measurement. The cases where the maximum velocity above and below the wake were not equal also indicate incomplete pressure recovery even at 20 per cent chord aft of the trailing edge of the test section. This problem was overcome by using a mean velocity as shown in Figure 10 and employing Jones' equation. This was found to be a reasonable approximation.

The integrating wake rake would give reasonable results if it spanned only the wake and did not extend into the free-stream regions above and below the wake where it senses the local velocity variations and interprets this as a component of drag. This means that the integrating wake rake results would be slightly higher than the results calculated from the wake velocity profiles. This is verified in the comparison of results in Figure 11. Reference 3 assumes that the static pressure is constant in the plane of measurement. This is true in the unsteady wake region but is not valid beyond the boundaries of the wake except perhaps one or two chord lengths downstream. The integrating wake rake system would therefore tend to give unreliable values of absolute profile drag. It is, of course, quite possible that this simple system could be used when compariative measurements only are required. For example, in studies concerning the effects of roughness on profile drag, the rake would remain in a constant position and the comparison results would then be quite reasonable.

The traversing wake rake gives excellent repeatable results, and its only disadvantage is that a certain time is necessary for the traverse. It is possible that flight conditions could change slightly during the course of the traverse; but this system can be dynamically balanced (which is a necessity for use on a sailplane), and the regions of unsteady flow can be detected very easily by the slight vibrations of the airspeed indicator. The traversing time problem could be overcome for powered aircraft work where a constant pressure altitude is maintained. A multi-Pitot-static tube rake connected to a multitube photographic manometer could then be used if considerable time was spent between tests for equilibrium conditions in the measuring systems to be attained; then the complete velocity profile could be found instantaneously.

The variations in static pressure above and below the wake indicate that at relatively high angles of attack, where the boundary layer near the trailing edge is thick and the profile drag considerable, the rear stagnation point is probably not located at the trailing edge of the airfoil but rather at some point in the wake. The determination of the location of this point is a necessity if calculations of the pressure distribution of high-lift airfoils are to be realistic.

CONCLUSIONS

The use of an integrating wake rake in conjunction with the report by Silverstein and Katzoff[3] for the determination of corrections to the profile drags tends to give unreliable results for distances behind the section trailing edge up to at least 20 per cent chord. It would appear that the integrating systems could be used when the plane of measurement was approximately one chord length behind the trailing edge; but for flight research this is not practical, as the size of the rake and the attachment problems would be considerable. The integrating systems could conceivably be used when comparative measurements only are required; but for absolute values of profile drag, a multi tube Pitot-static rake or a traversing Pitot-static probe should be used to determine the wake velocity profile.

The traversing Pitot-static probe gave excellent repeatable results and is recommended for sailplane work where continuous pressure changes occur because the system can be easily balanced. Where continuous pressure changes do not occur, for example, on powered aircraft at constant altitude or in wind-tunnel experiments, the multi tube Pitot-static system would give adequate wake velocity profiles from which profile drags may be calculated using Jones equation. This means that the plane of measurement can be quite close to the section trailing edge.

It is recommended for future work on calculations of the pressure distributions of high-lift airfoil sections that experiments to determine the exact location of the rear stagnation point be performed and the results correlated with boundary layer thickness at the trailing edge, angle of attack, and Reynolds number.

REFERENCES

1. Betz, A., "Ein Verfahren Zer Direuten Ermittlung Des Profiliwiderstandes".

2. Jones, B. M., "Measurement of Profile Drag by the Pitot Traverse Method", ARC R&M 1688 (1936).

3. Silverstein, A., and Katzoff, S., "A Simplified Method for Determining Wing Profile Drag in Flight", Proceedings of the Eighth Annual Meeting, IAS, Jan. 1940.

4. Roberts, S. C., "Flight Testing of the Marvel and Marvelette Airfoil Section", Aerophysics Department, Mississippi State University Research Report No. 38, 1962.

5. Squire, H. B., "Variations of Profile Drag with Incidence", A.R.C. R&M 2239 (1946).

APPENDIX

The following is the program for the IBM 1620 to determine the profile drag of an airfoil section from the wake velocity profiles using the equation derived by Jones.[2]

IBM 1620 FORGO, FORTRAN

INPUT:

Card 1:

4 words per card
Format (3F12.4,I3)

UMAXM (Umax in mph)
UINFM (U_∞ in mph)
CHORD (Chord in ft.)
N (No. values of y)

Card 2 - n:

6 words per card, maximum 10 cards
Format (6F12.4)

YIN (y in inches)

Cards n + 1 - 2n - 1:

6 words per card, maximum 10 cards
Format (6F12.4)

UMPH (u in mph)

OUTPUT:

Card 1:

4 words per card, maximum 1 card
Format (F12.8,3F12.4)

CDO (C_{D_O})
UINFM (U_∞ in mph)
UMAXM (Umax in mph)
CHORD (Chord in feet)

SYMBOLS:

YIN	y in inches
Y	y in feet
UMPH	u in mph
U	u in fps
UMAXM	Umax in mph
UINFM	U_{∞} in mph
UIN	U_{∞} in fps
CHORD	Chord in feet
XSQ	$K^2 = 1 - (Umax/U_{\infty})^2$
UPLOT	$u(1 - \sqrt{K^2 + (u/U_{\infty})^2})$
AREA	$u\ (1 - \sqrt{K^2 + (u/U_{\infty})^2}\ dy$

```
C  C  IBM 1620 FORGO, VELOCITY DEFECT
     1 DIMENSION YIN (60), UMPH (60), U(60), UPLOT (60), Y (60)
     2 READ 102, UMAXM, UINFM, CHORD, N
   102 FORMAT (3F12.4,I3)
     3 READ 103, (YIN(I),I=1, N)
   103 FORMAT (6F12.4)
     4 READ 103, (UMPH(I), I=1, N)
     5 DO 7 I=1, N
     6 Y(I)=YIN(I)/12.
     7 U(I)=UMPH(I)*1.467
     8 XSQ=1.-(UMAXM/UINFM)**2
     9 UIN=UINFM*1.467
    10 DO 11 I=1, N
    11 UPLOT (I)=U(I)*(1.-SQRTF(XSQ+(U(I)/UIN)**2))
    12 AREA = 0.0
    13 NMI = N-1
    14 DO 15 I = 1, NMI
    15 AREA = AREA+((UPLOT (I+1)+UPLOT(I))/2.)*(Y(I+1)-Y(I))
    16 CDO = (2./(CHORD*UIN))*AREA
    17 PUNCH 217, CDO, UINFM, UMAXM, CHORD
   217 FORMAT (F12.8, 3F12.4)
    18 GO TO 2
       END
```

IBM 1620 FØRGØ, FØRTRAN

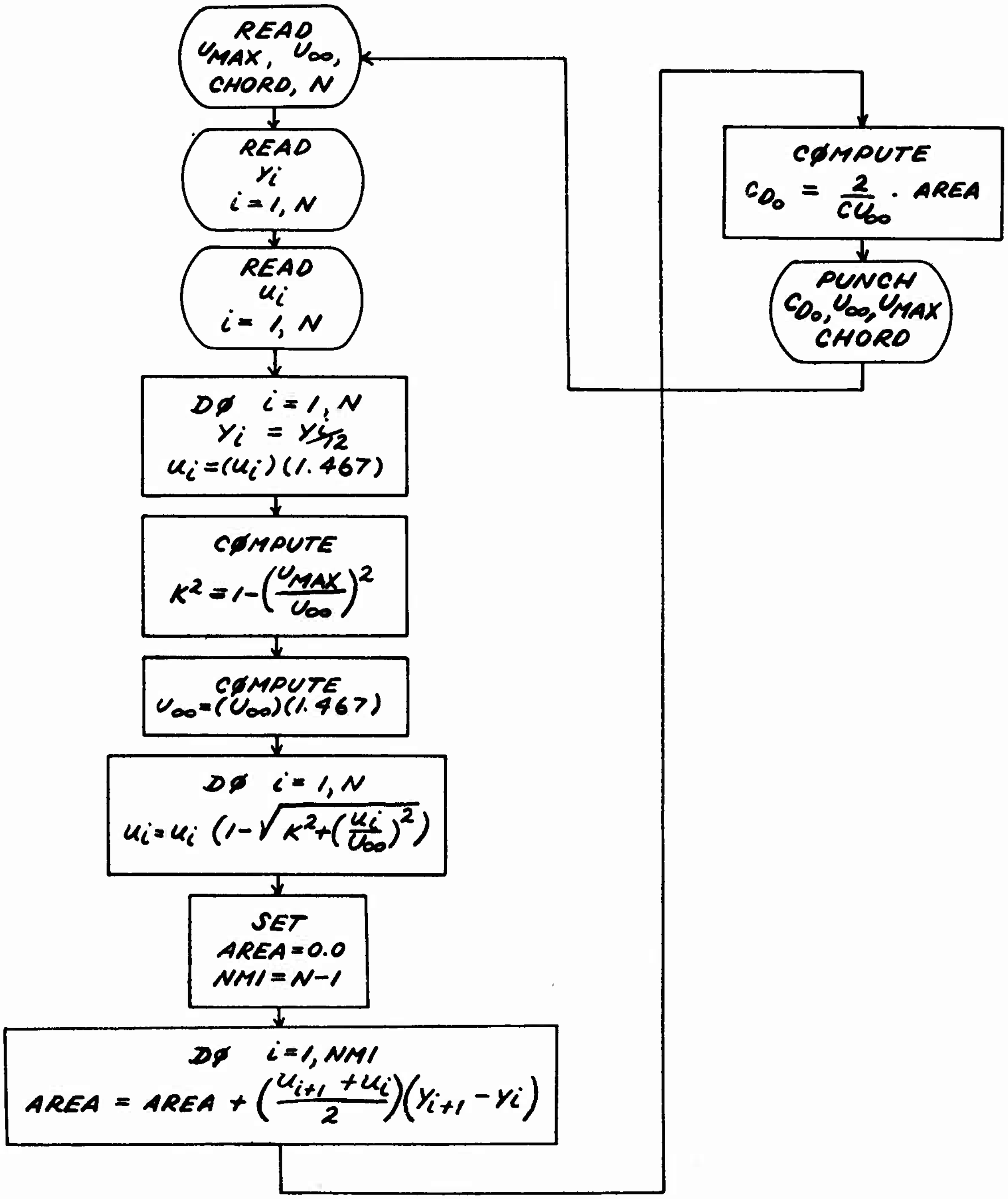
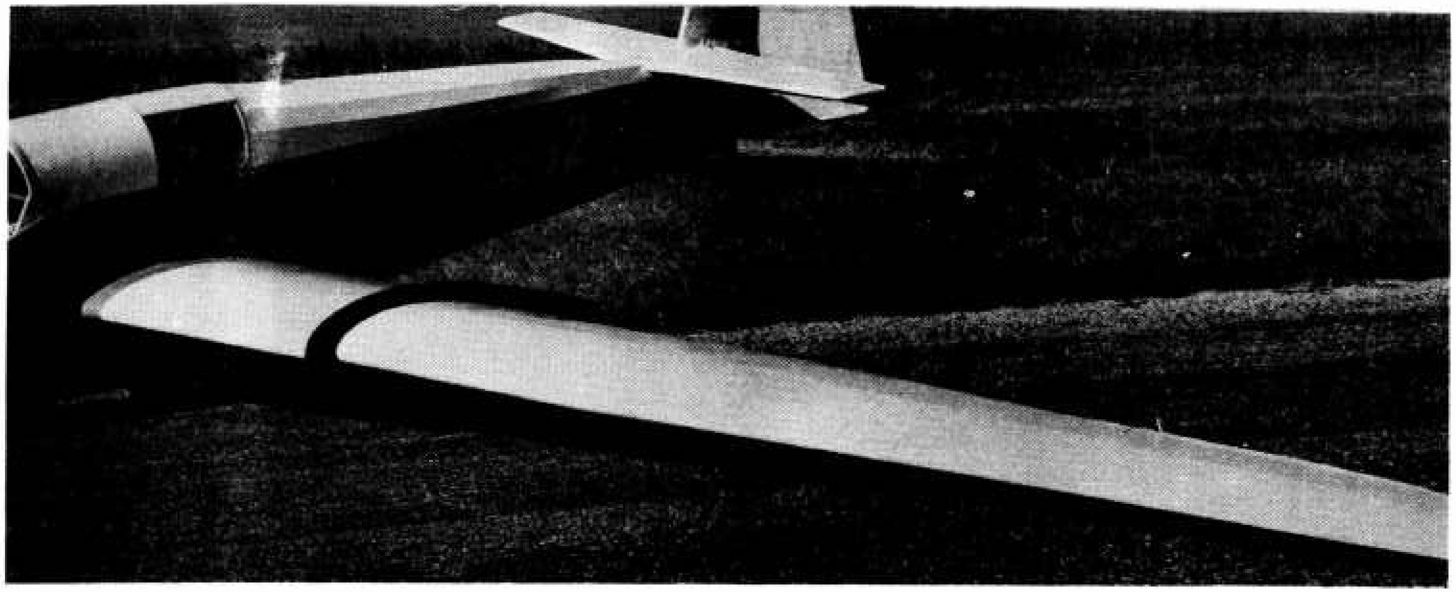


Figure 1. General View of Sailplane Showing Both Test Sections.



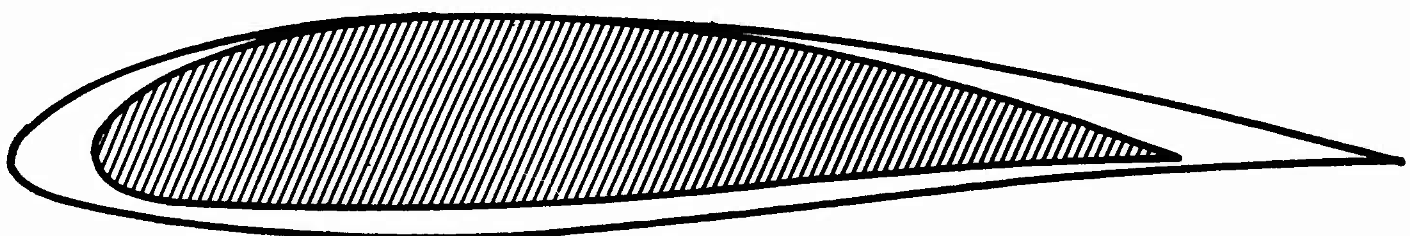
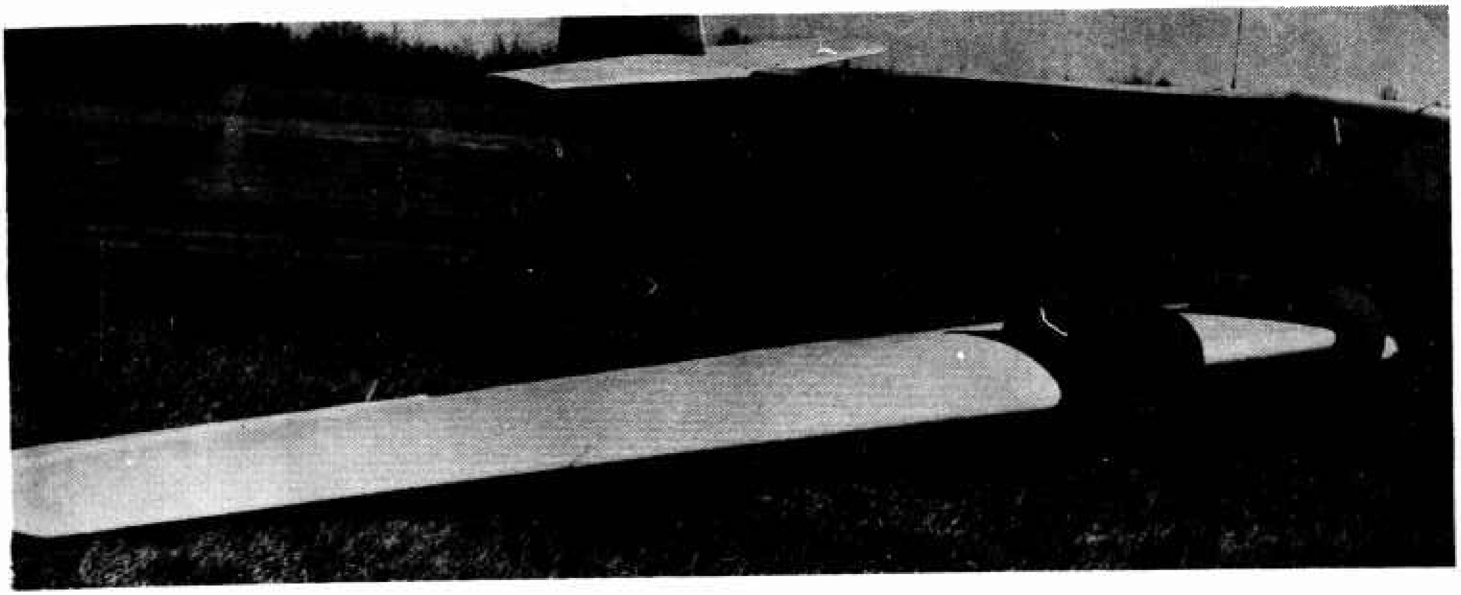


Figure 2. Airfoil Test Section #1 on Port Wing of Sailplane.



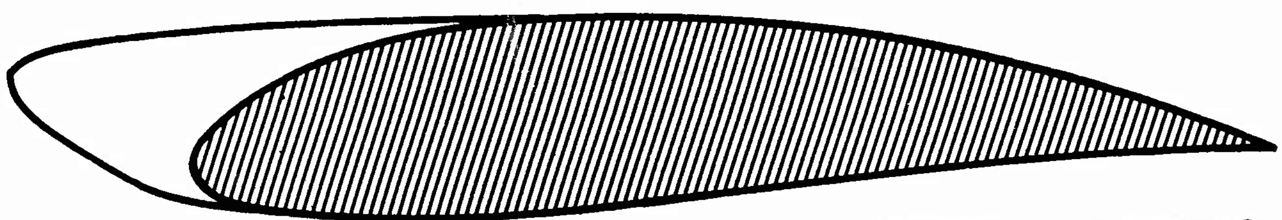


Figure 3. Airfoil Test Section #2 on Starboard Wing of Sailplane.

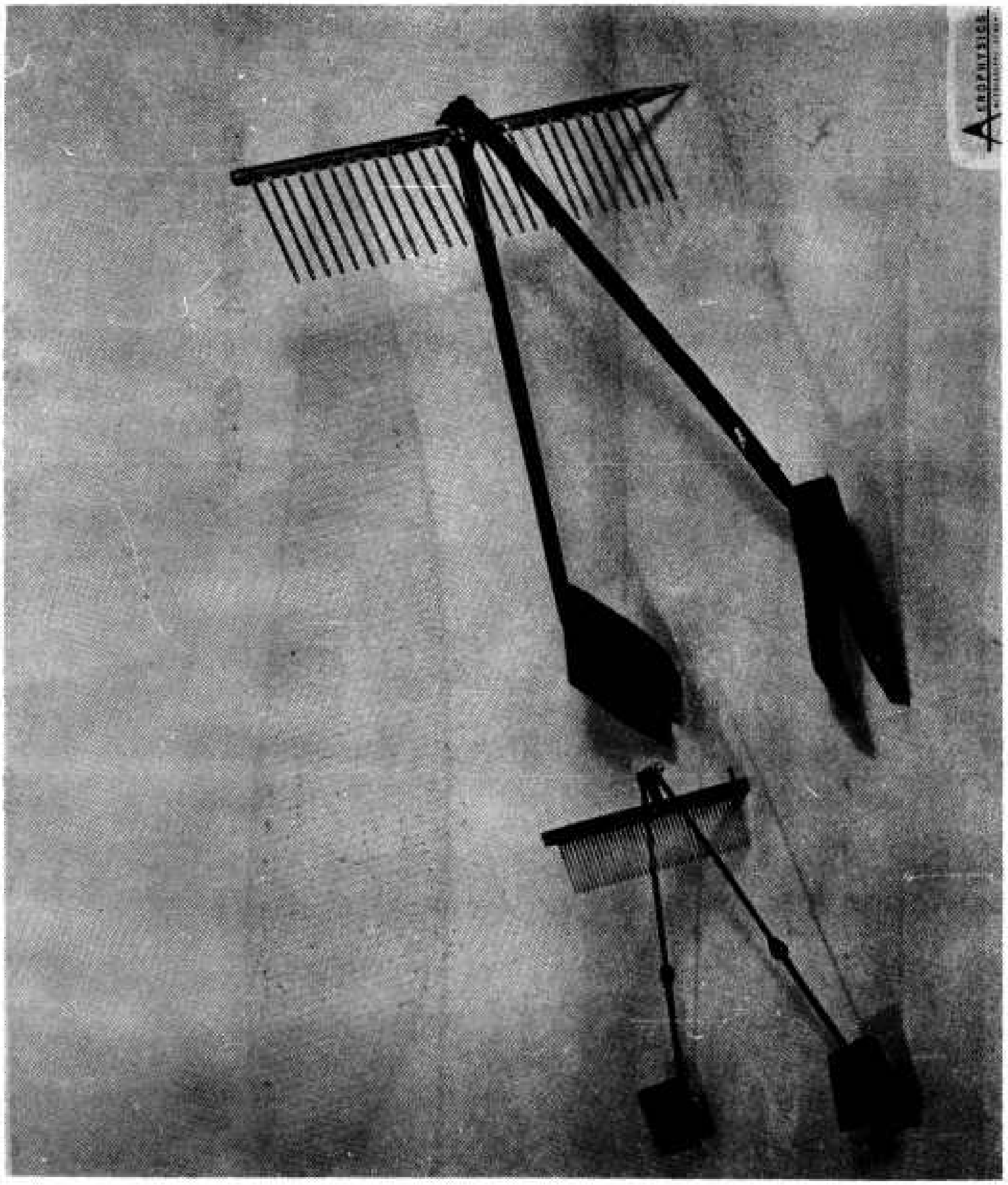


Figure 4. The Small and Large Integrating Wake Rakes.

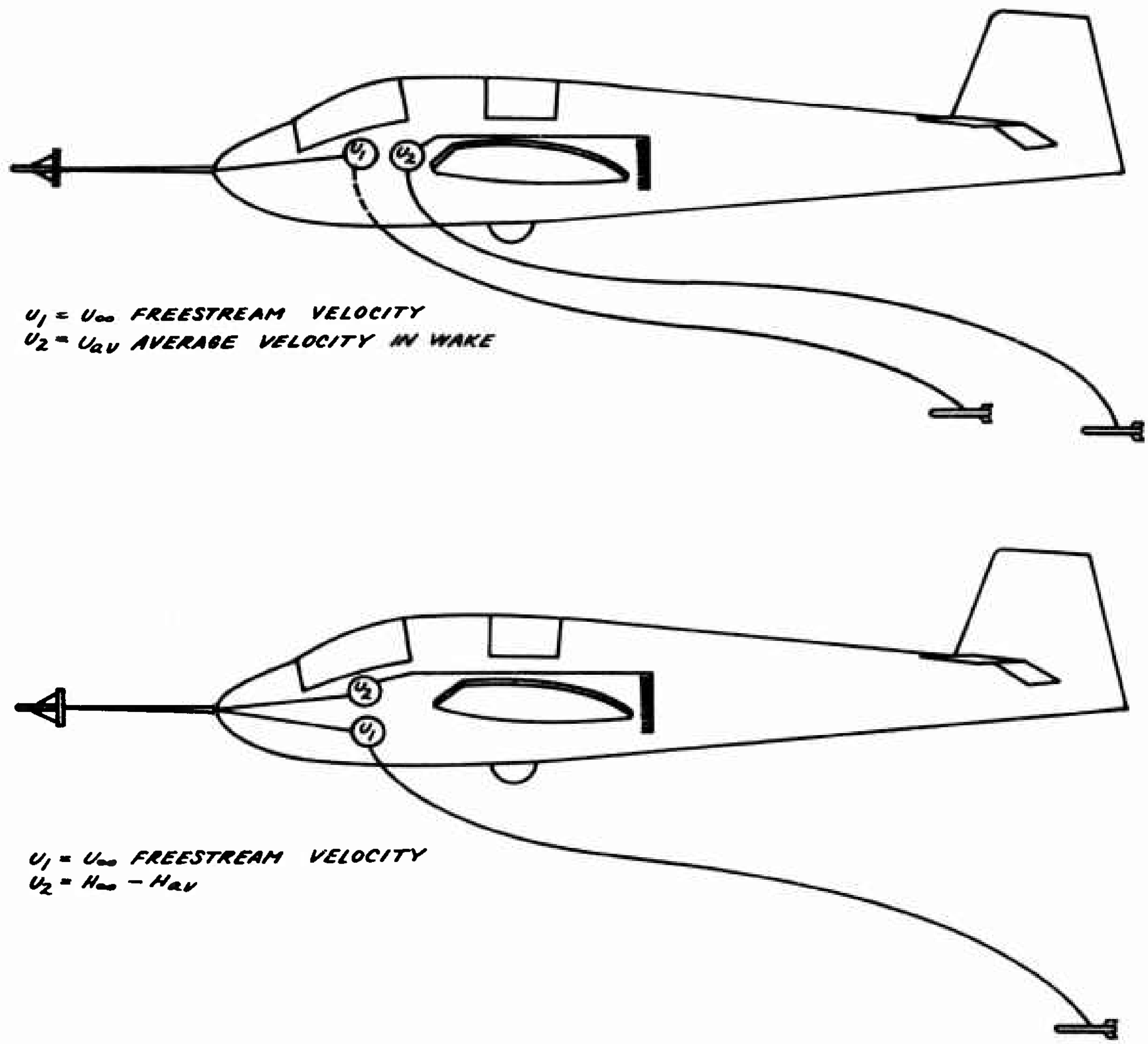


Figure 5. Diagrammatic Sketch of Integrating Wake Rake Connections.

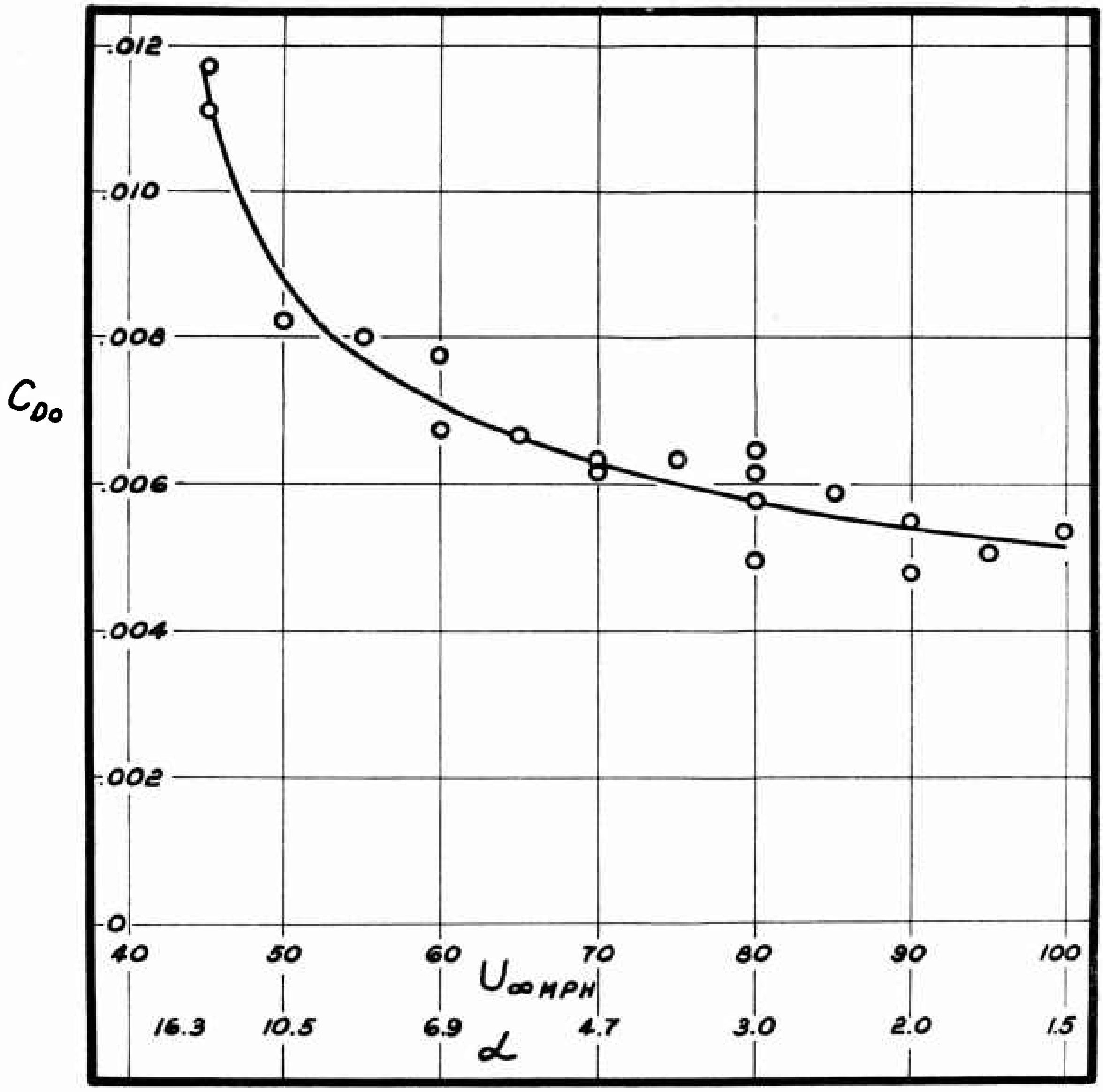


Figure 6. Profile Drag Curve, #1 Airfoil Section (small integrating wake rake).

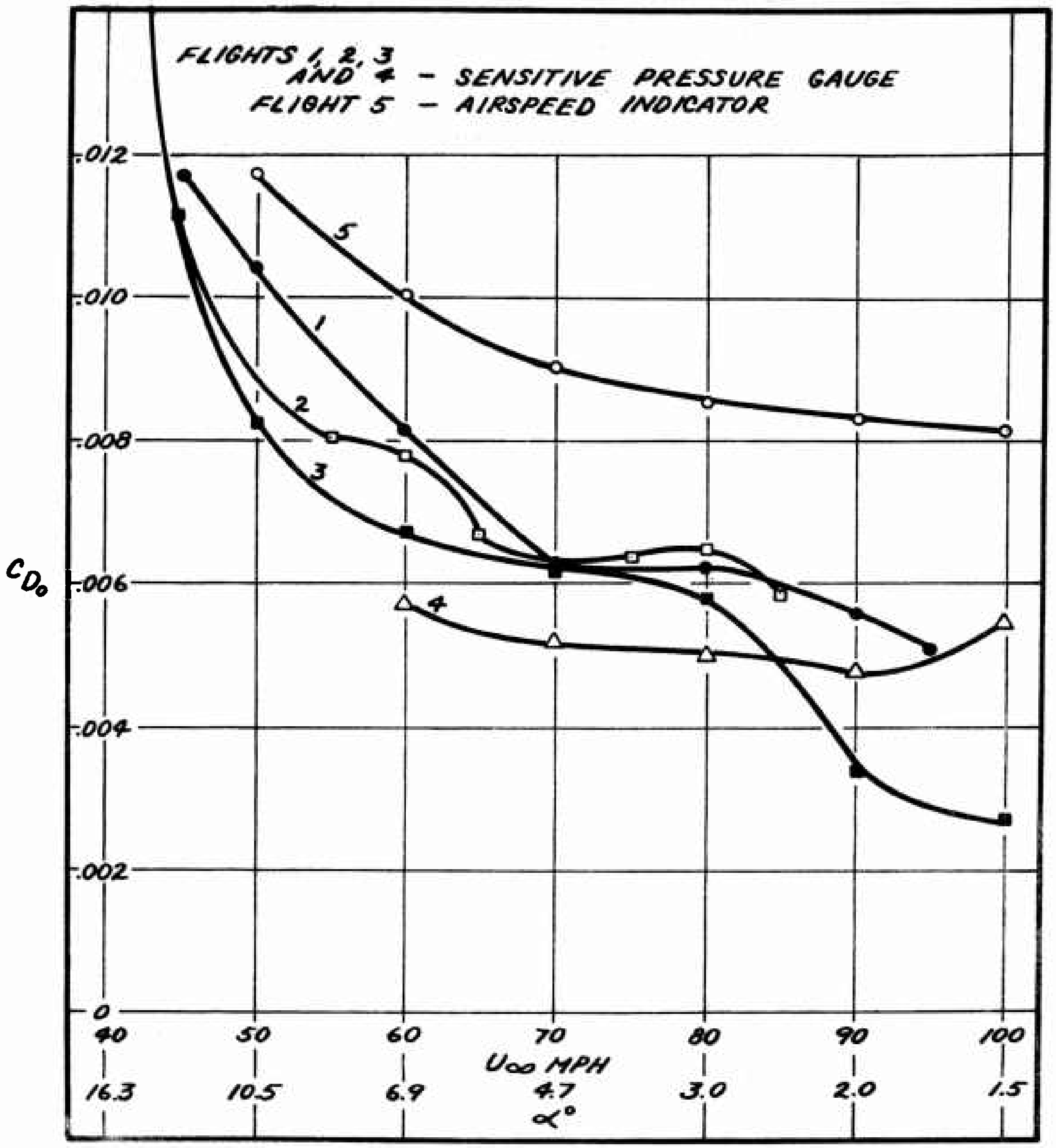


Figure 7. Profile Drag Curve, #1 Airfoil Section Using Both a Sensitive Pressure Gauge and an Airspeed Indicator.

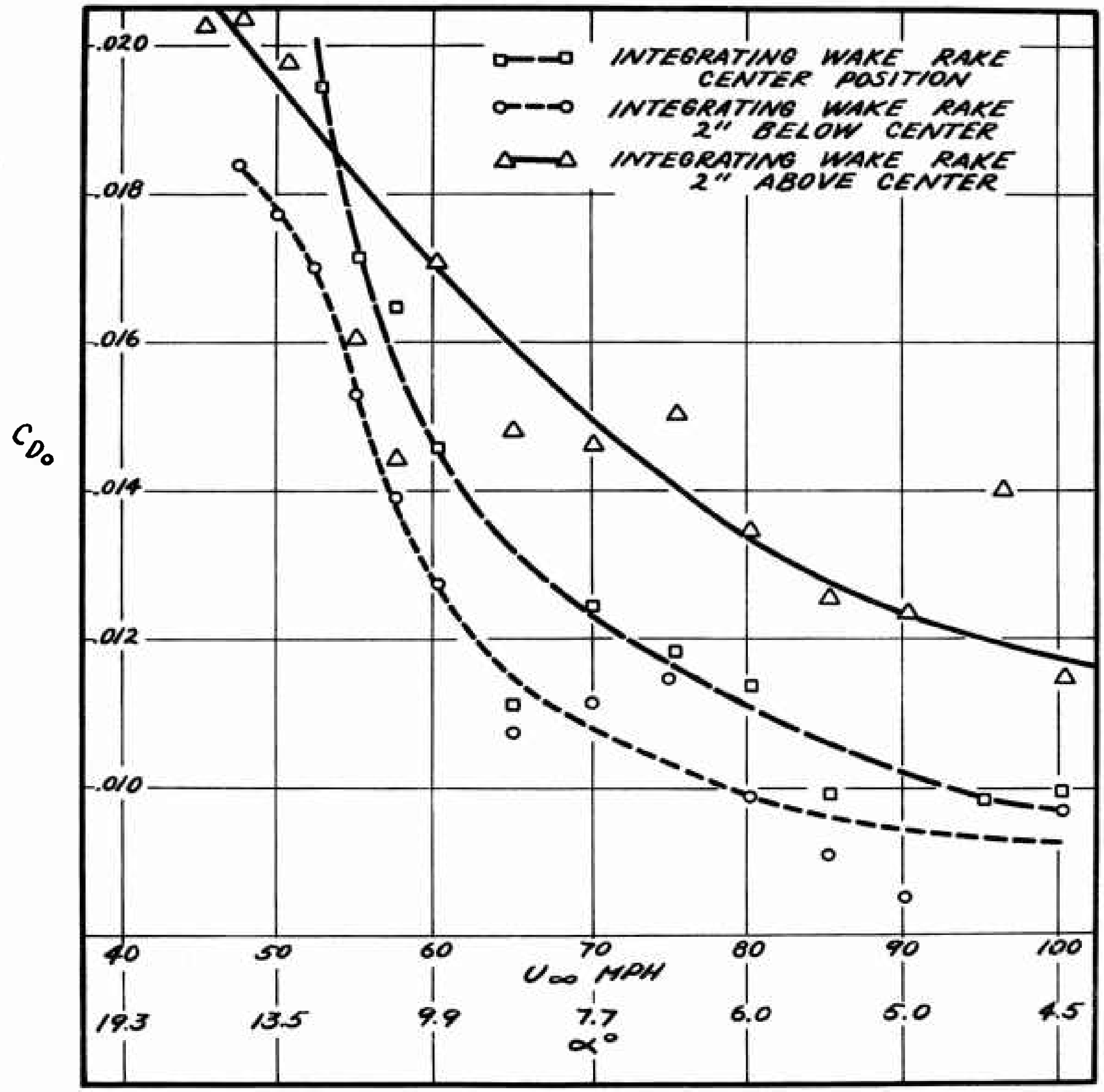


Figure 8. Profile Drag, #2 Airfoil Section (large integrating wake rake).

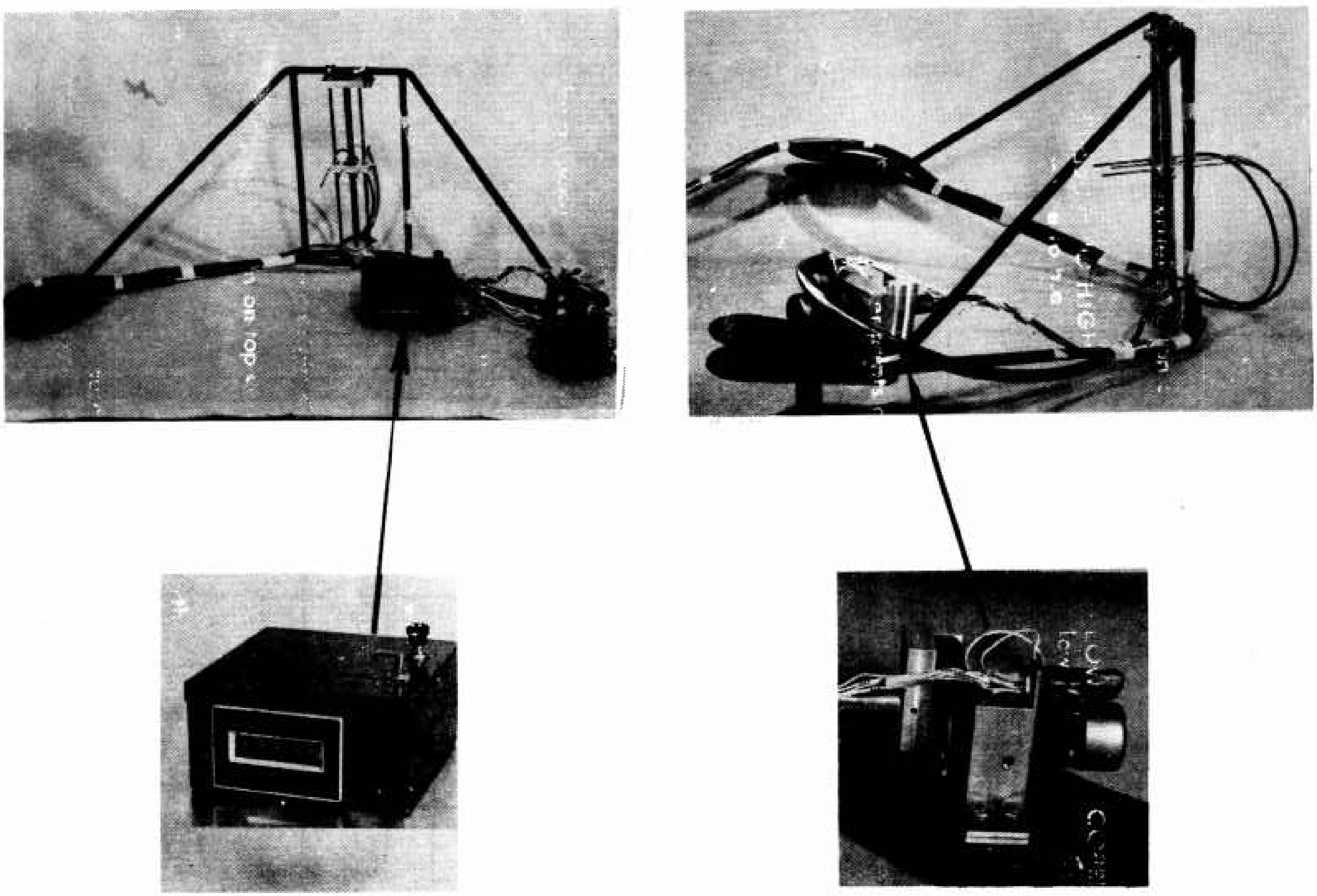


Figure 9a. Tranversing Wake Rake; General Views.

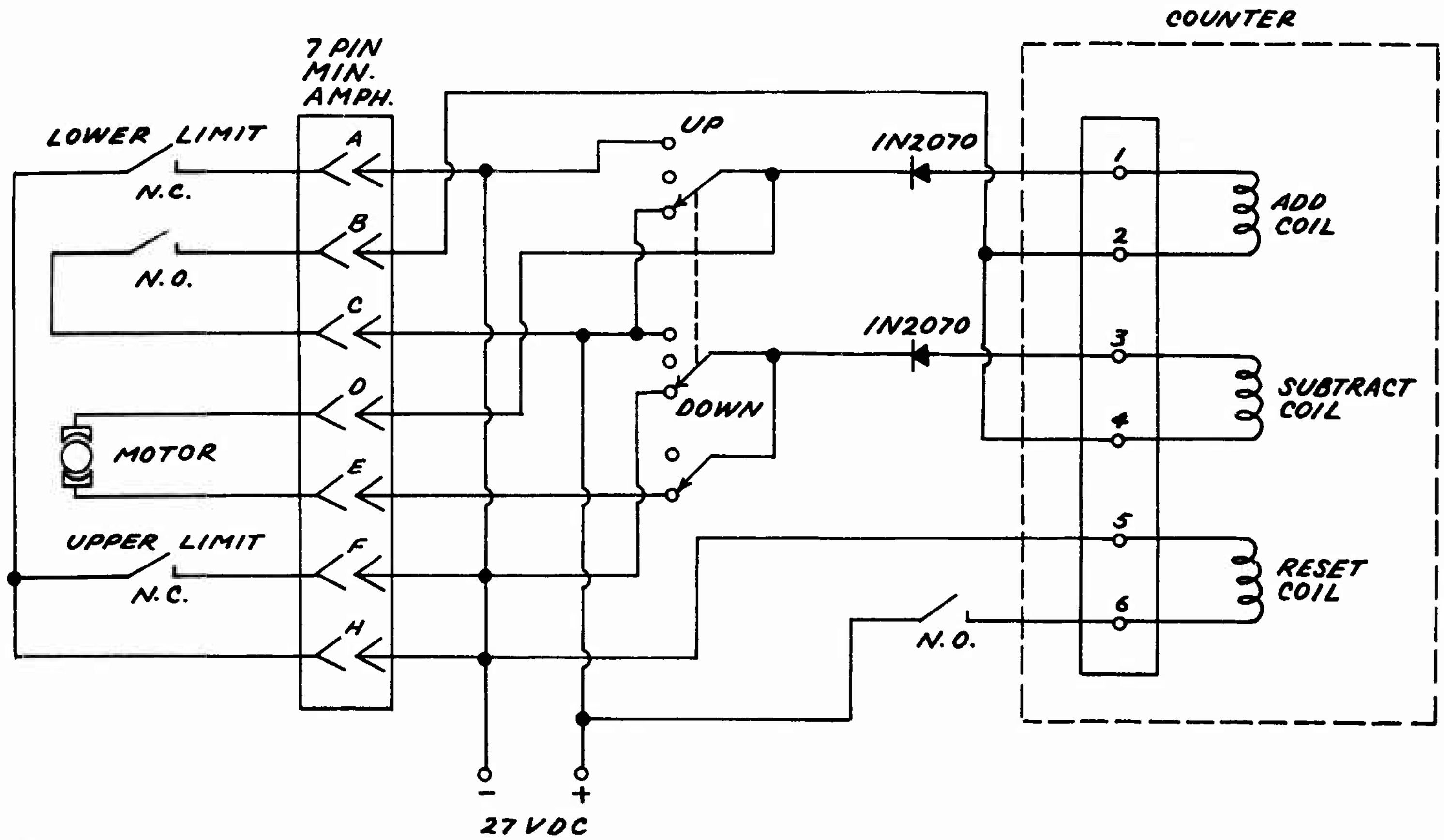


Figure 9b. Traversing Wake Rake; Wiring Diagram.

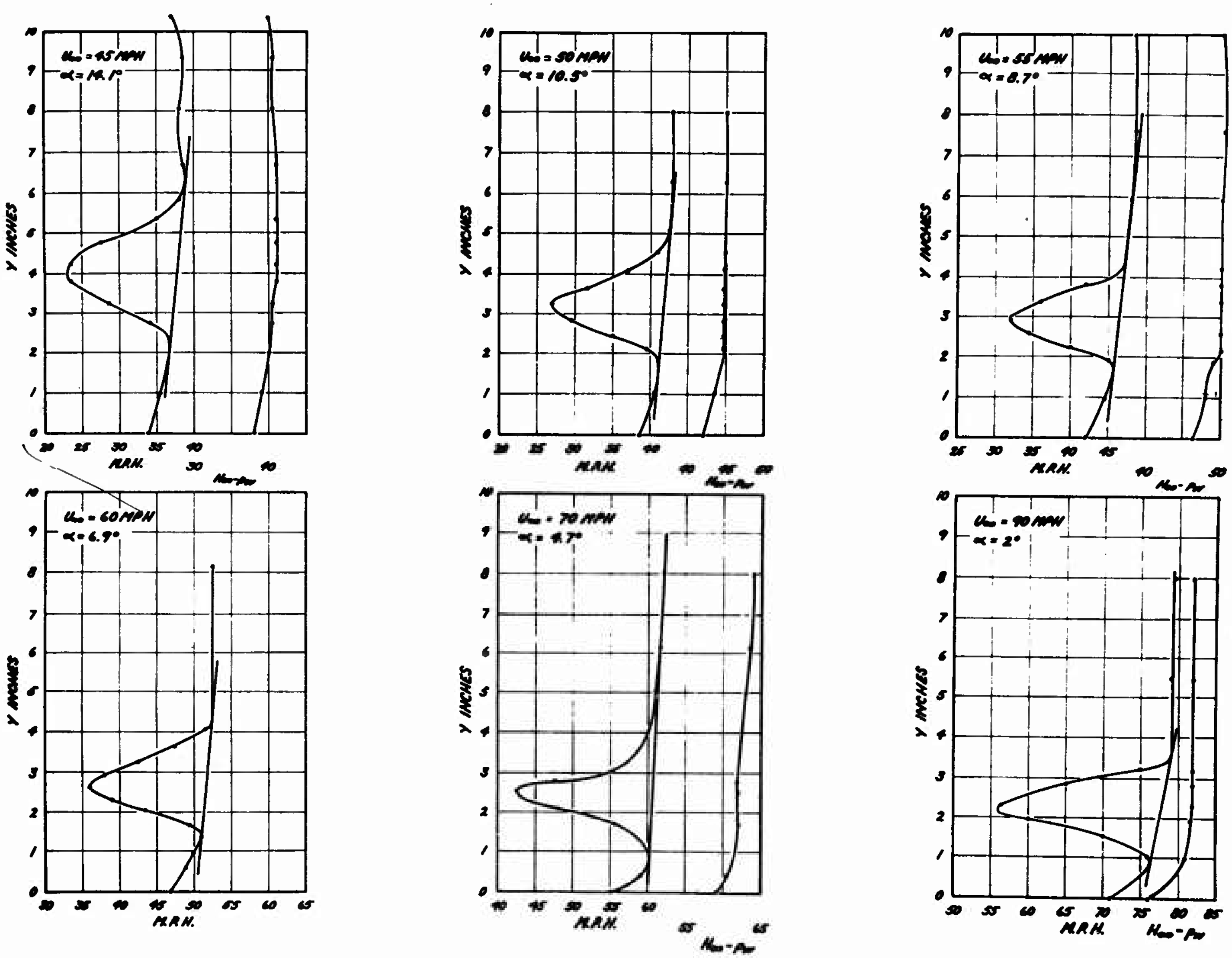


Figure 10. Wake Velocity Profiles, #1 Airfoil Section.

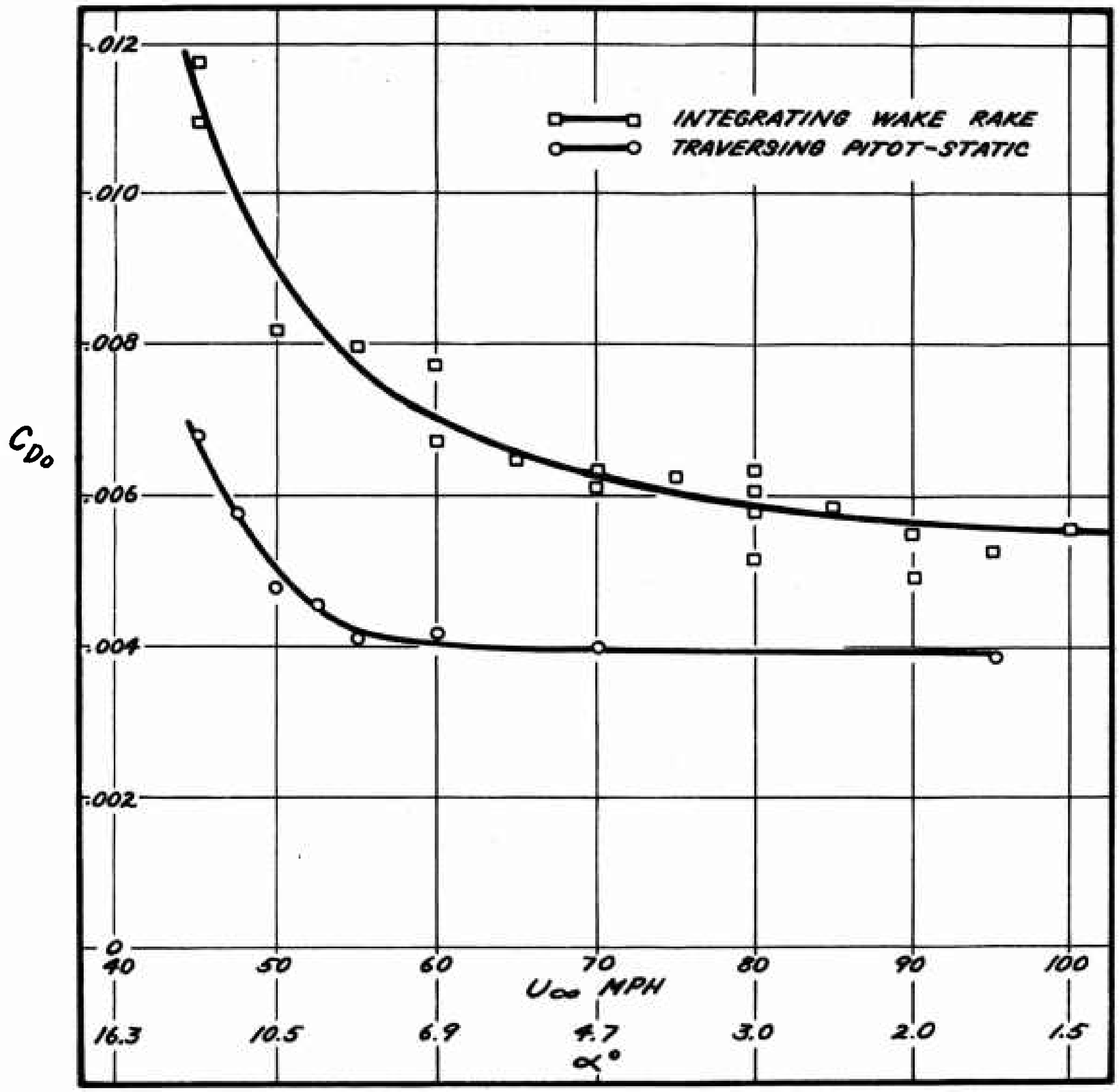


Figure 11. Comparison of Profile Drags, #1 Airfoil Section.

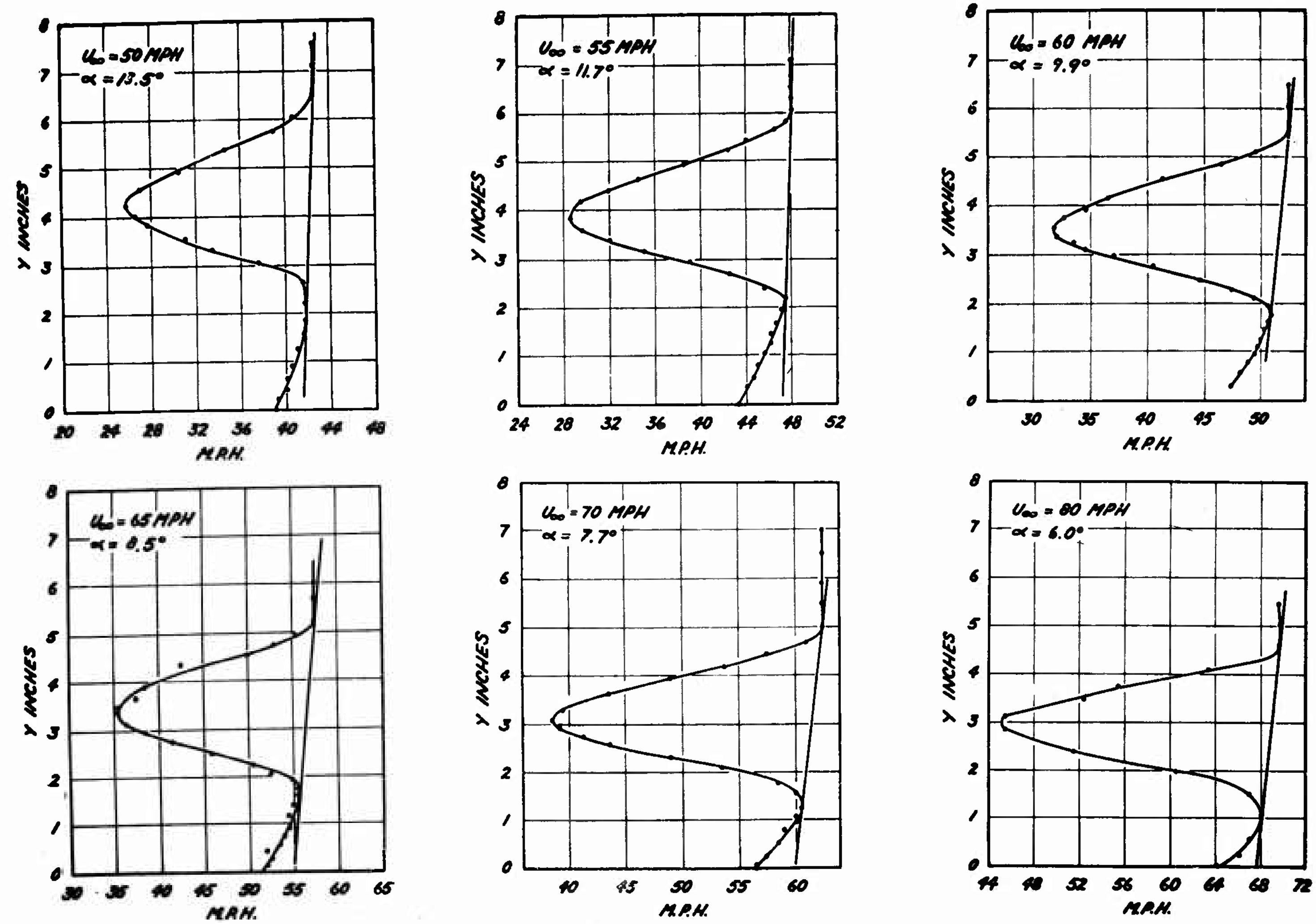


Figure 12. Wake Velocity Profiles, #2 Airfoil Section.

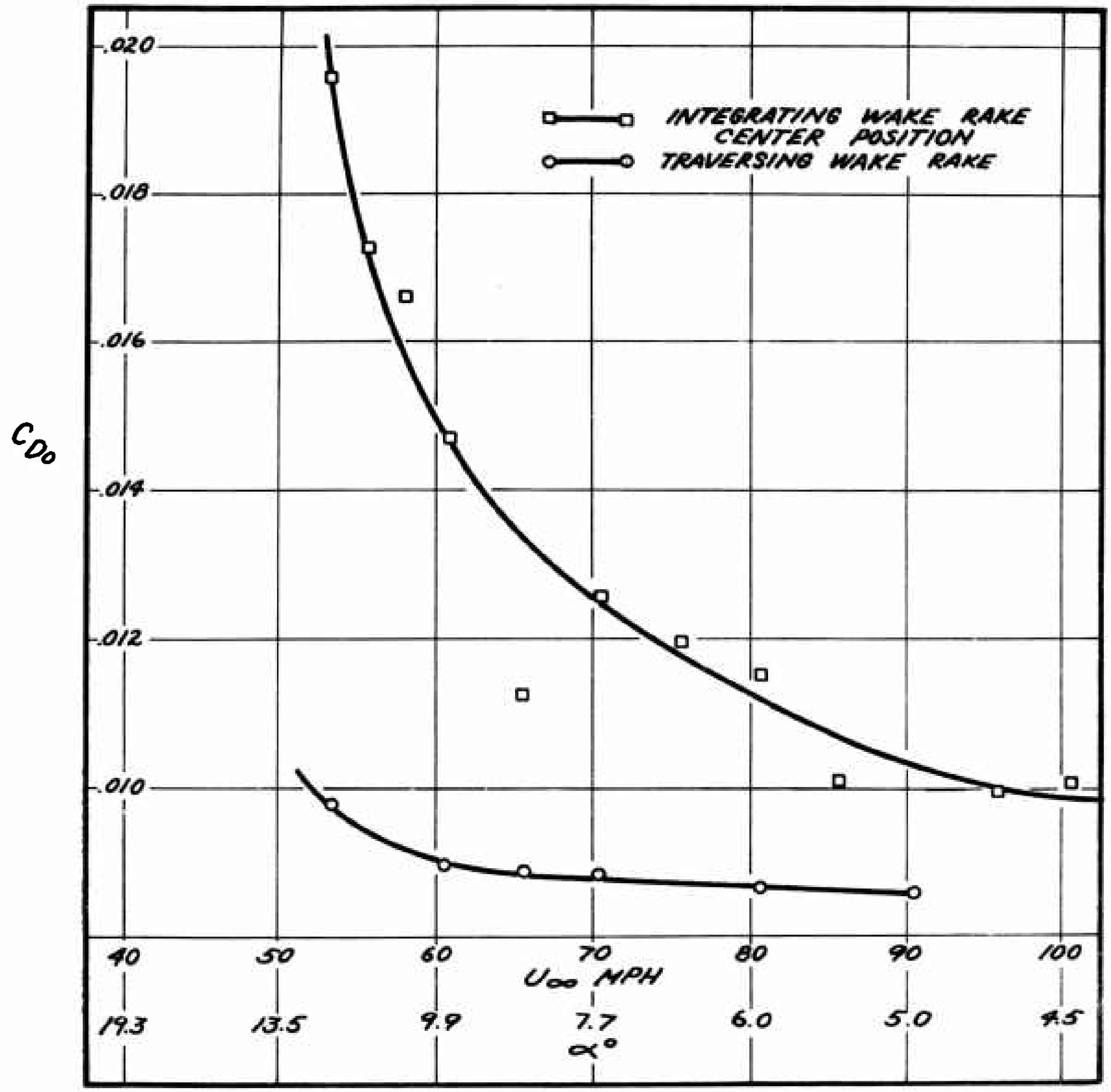


Figure 13. Comparison of Profile Drag, #2 Airfoil Section.

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2. Aerodynamics

Unclassified Report

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